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The emissions from a space-heating biomass stove

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Abstract

In this paper, the flue gas emissions of carbon monoxide (CO), nitrogen oxides (NO_X), sulphur dioxide (SO_2) and soot from an improved space-heating biomass stove and thermal efficiency of the stove have been investigated. Various biomass fuels such as firewood, wood shavings, hazelnut shell, walnut shell, peanut shell, seed shell of apricot (sweet and hot seed type), kernel removed corncob, wheat stalk litter (for cattle and sheep pen), cornhusk and maize stalk litter (for cattle pen) and charcoal were burned in the same space-heating biomass stove. Flue gas emissions were recorded during the combustion period at intervals of 5 min. It was seen from the results that the flue gas emissions have different values depending on the characteristics of biomass fuels. Charcoal is the most appropriate biomass fuel for use in the space-heating biomass stoves because its combustion emits less smoke and the thermal efficiency of the stove is approximately 46%.

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Keywords: Space-heating stove; Biomass-fired stove; Biomass fuels; Stove emission; Combustion; CO; NO_X; SO_2; Soot; Thermal efficiency

1. Introduction

Biomass is the main source of domestic energy in developing countries. In order to use biomass fuels as a source of heat, biomass stoves are needed. Traditional biomass stoves have less thermal efficiency and high flue gas emissions compared with improved stoves. However, biomass stoves generally emit high flue gas emissions because of the formation and properties of the biomass fuels. The flue gases from these stoves cause serious health problems and environmental air pollution [1–5]. In a biomass stove combustion chamber, a number of physical and chemical processes occur in time and space during the combustion. The processes include: drying and preheating of the fuel, pyrolytic release of volatile flammable matter, flaming combustion of the pyrolyzates and glowing combustion of fixed carbon. Besides, the products of biomass combustion should generally contain carbon dioxide, water, ash, sulphur oxides, carbon monoxide, unburnt hydrocarbons, oxides of nitrogen, smoke and soot [6].

In this paper, we report the results of a study on flue gas emissions from an improved space-heating biomass stove and the thermal efficiency of the stove. We determined the carbon monoxide (CO), nitrogen oxides (NO_X), sulphur dioxide (SO_2) and soot emissions of 12 different biomass fuels. The total emissions (amount of emitted substance per MJ of heat obtained from burnt fuel) of biomass fuels are discussed.

2. Materials and methods

It was aimed to determine the air pollution (CO, NO_X, SO_2 and soot) from an improved biomass stove largely manufactured and used for space heating in developing countries and thermal efficiency of the stove in this study. All experiments were conducted in winter. A room was selected for tests. Its measurements were (width, length, height) 6, 11, 5 m. Twelve different types of biomass fuels extensively used for space heating in developing countries were selected for this experimental investigation. These biomass fuels are: firewood (*Quercus infectoria*), wood shavings (*Quercus infectoria)*, hazelnut shell (*Corylus avellana* L.), walnut shell (*Juglans regia* L.), peanut shell (*Arachis hypogaea*), seed shell of apricot (sweet and hot

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Nomenclature

A	top, bottom or vertical surface area of the stove, or stovepipe surface area, m^2
a,m	constants for calculating Nu
c_c	calorific value of the fuel used for the experiments, $J\,kg^{-1}$
g	gravitational acceleration, $m\,s^{-2}$
Gr	Grashof number
h_c	convective heat transfer coefficient, $W\,m^{-2}\,{}^{\circ}C^{-1}$
h_r	radiative heat transfer coefficient, $W\,m^{-2}\,{}^{\circ}C^{-1}$
k	thermal conductivity, $W\,m^{-1}\,{}^{\circ}C^{-1}$
L	height, m
m_c	mass of the fuel used for each experiment, kg
m_n	net mass of the burnt fuel in one heating period, kg
m_s	mass of the unburnt solids, kg
Nu	Nusselt number
Pr	Prandtl number
Q	total useful heat, J
Q_{av}	average useful heat of the stove, J
q_c	convective heat transfer from the external surface of the stove and stovepipe to the room air, W
$Q_{\text{ex-1}}$, $Q_{\text{ex--2}}$	Useful heat of the stove calculated from experinet I and experiment II, J
Q_f	heat liberated from the *fuel*, J
q_r	radiative heat transfer, W
t	a heating period (an experiment) time, s
T_s, T_a	surface temperature of the stove or stovepipe, and air temperature in the room, °C
T_w, T_r	absolute temperatures of the stove or stovepipe and room surfaces, K

Greek symbols

β	coefficient of thermal expansion, K^{-1} (β is evaluated at the mean film temperature $T_f = (T_s + T_a)/2$
ε	emissivity of the stove and stovepipe, 0.97
σ	Stefan–Boltzman constant (5.67×10^{-8} $W\,m^{-2}\,K^{-4}$)
η	the thermal efficiency of the stove, %
η_{av}	average thermal efficiency of the stove, %
$\eta_{\text{ex-1}}$, $\eta_{\text{ex-2}}$	thermal efficiency of the stove obtained from experiment I and experiment II, %
v	kinematic viscosity, $m^2\,s^{-1}$
ΔT	temperature differences between surface of the stove or stovepipe and room air, °C

seed type) (*Prunus armeniaca* L.), kernel removed corncob (*Zea mays indentata* Sturt), wheat stalk litter (*Triticum aestivum*) (for cattle and sheep pen), cornhusk and maize stalk litter (*Zea mays indentata* Sturt) (for cattle pen) and charcoal (*Quercus infectoria*). These fuels were collected from various regions of Turkey in different seasons. Natural open sun drying technique was applied as post treatment to remove the excessive water from biomass fuels. These were stored in plastic bags until the time of experiments. The characteristics of selected biomass fuels are given in Table 1. Most of these characteristics were measured and determined by us. Several specifications of few of these fuels were also obtained from different literatures [7,8]. The experimented stove contains several main parts. It mainly has a steel sheet (bucket) firebox (fuel bed) with front fresh air regulating damper, primary and secondary air inlet channels, ash pan (ash bed), outer wall steel sheet and steel grate (Fig. 1). All other technical specifications of the stove are also given in Table 2. The stove was placed 20 cm from the room floor on a metal floor protection pad to ensure that ash and embers do not soil the floor rug and also to shield the floor covering from radiant heat. A sheet-metal stovepipe (diam. 13 cm) was connected to the exhaust pipe to lead flue gas out of the room. The stove bucket (fuel bed) was filled with biomass fuel for each experiment. Each type of fuel was tested twice for two heating periods (two times). During all experiments the primary and secondary air inlet channels were kept open. The emissions of CO, NO_X, SO_2 and soot of flue gases were measured at proper points (Fig. 2). After the biomass fuel was ignited, the emissions were recorded at an interval of 5 min. Since particle size is a critical parameter in the combustion, we kept the piece-size of the each biomass fuel constant depending on their physical characteristics from one experiment to another. The entire charge was completely burnt within 10–120 min depending on the formation and characteristics of the biomass fuels. After the ash was removed, the stove was refilled and lighted again for the next experiment. In order to measure the flue gas emissions an MRU 95/3CD type electrochemical flue gas analyzer was used. The emissions of CO, NO_X, SO_2 flue gases were measured electrochemically and the soot was measured with a smoke-shade type measurement by using the same device. The flue gas analyzer was firstly used for this experimental investigation when it had factory settings and calibration. The approximate life of sensors of the device are offered 24 months for all emissions measured in this study. Measurement of room temperature (°C), gas temperature (°C), CO ($mg\,m^{-3}$), NO_X ($mg\,m^{-3}$) and SO_2 ($mg\,m^{-3}$) was completed in a half-month for the whole experiments. The soot was defined as black color (number: 9: maximum soot) and white color (number: 0: no soot) or between these two colors (1: little soot, 2, 3, 4, 5, 6, 7, 8: much soot). Therefore, the amount of soot in the flue gas was given as a number between 0 and 9 for comparison. Besides, the thermal efficiency of the stove was determined. In order to calculate the efficiency, the temperature distribution of the stove and stovepipe

Table 1
Characteristics of selected biomass fuels

Fuels	Moisture (%)	Ash (%)	Density ($kg\,m^{-3}$)	Calorific value ($kJ\,g^{-1}$)	Burning rate ($kg\,h^{-1}$)
Firewood	11.28	5.24	301	19.00	4.28
Wood shavings	6.25	0.97	103	19.00	2.86
Hazelnut shell	13.95	1.38	292	19.00	5.42
Walnut shell	11.14	2.05	275	15.00	4.80
Peanut shell	2.63	2.20	83	15.25	2.88
Seed shell of apricot (sweet seed type)	10.09	5.95	463	21.80	4.73
Seed shell of apricot (hot seed type)	12.67	6.94	441	21.80	6.64
Kernel removed corncob	15.60	1.50	196	12.45	3.66
Wheat stalk litter (for cattle pen)	4.94	20.05	37	11.50	4.62
Wheat stalk litter (for sheep pen)	3.79	18.54	37	11.54	3.98
Cornhusk and maize stalk litter (for cattle pen)	4.21	20.73	32	11. 30	3.87
Charcoal	4.14	5.86	291	19.25	1.13

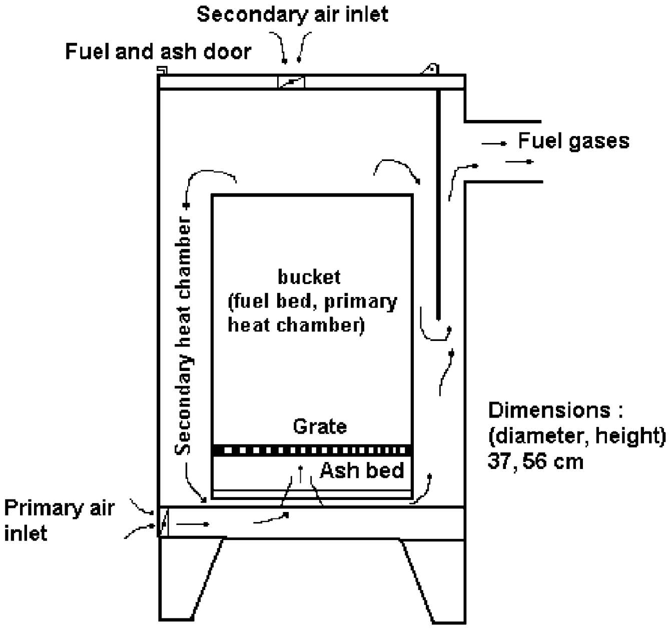

Fig. 1. Schematic diagram of the improved space-heating biomass stove.

Table 2
Technical features of the selected biomass stove

Features	İmproved space-heating biomass stove
Year of design	2000
Cost ($)	50
Estimated lifetime (years)	3–4
Mass (kg)	33
Construction material	Cast iron steel sheet
Number of steel grate	1
Ash pan	No
Bucket	Yes
Size (width, length, height or diameter, height) (cm)	37, 56

surfaces were measured at proper points (per 1.0 m) throughout the length (6 m) of the stovepipe by using a digital infrared thermometer. The experimental enclosure was calibrated by using another heater (Fig. 3). This means that, the temperature of the experimental enclosure was kept constant during all the experiments. This is needed to eliminate the effect of heat flows from walls to outside and to determine the exact temperature differences between the stove–stove pipe and experimental enclosure for calculating the efficiency sensitively. The experimental runs were terminated when the flue gas temperature dropped below 100 °C at the outlet of the chimney. The flue gas temperature was measured by a thermocouple. To determine the thermal efficiency of the stove, it is needed to find the total useful heat. The heat generated in the stove during combustion is delivered to the room by natural convection and radiation from the hot surfaces of the stove and stovepipe. The convective and radiativa heat transfer coefficients from the exterior surfaces of the stove and stovepipe to the room can be calculated as follows [9–12].

$$Gr = (g\beta \Delta T\,L^3)/v^2, \tag{1}$$

$$Nu = a(\mathrm{Gr}\,Pr)^m, \tag{2}$$

$$h_c = (Nu\,k)/L, \tag{3}$$

$$\mathrm{hr} = [\sigma\varepsilon(T_w^4 - T_r^4)]/(T_w - T_r). \tag{4}$$

Total useful heat and the effciency can also be given as follows [9,10,13].

$$q_c = h_c A(T_s - T_a), \tag{5}$$

$$q_r = h_r A(T_w - T_r), \tag{6}$$

$$Q = (q_c + q_r)t, \tag{7}$$

$$Q_{av} = (Q_{ex\text{-}1} + Q_{ex\text{-}2})/2, \tag{8}$$

$$\eta = (Q/Q_f)100, \tag{9}$$

$$\eta_{av} = (\eta_{ex\text{-}1} + \eta_{ex\text{-}2})/2, \tag{10}$$

$$Q_f = m_n c_c, \tag{11}$$

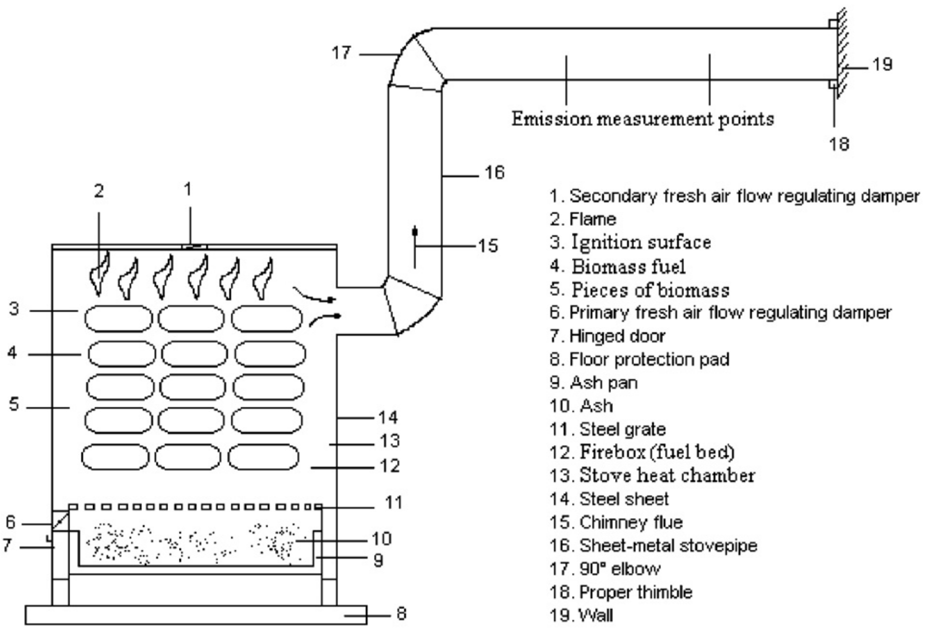

Fig. 2. The working principle of the selected biomass stove and flue gas emission measurement points.

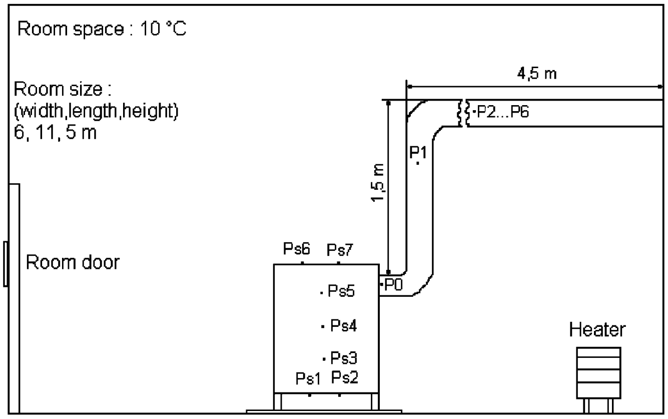

Fig. 3. Temperature measurement points of the stove and stovepipe surfaces.

$$m_n = m_c - m_s. \tag{12}$$

3. Results and discussion

In this study, we measured and determined the biomass flue gas emissions of carbon monoxide, nitrogen oxides, sulphur dioxide and soot. The results regarding CO, NO_X and SO_2 emissions of firewood, wood shavings, hazelnut shell, walnut shell, peanut shell, seed shell of apricot (sweet and hot seed type) and kernel removed corncob as a function of burning time are given in Figs. 4–6. The total flue gas emissions (amount of emitted substance per MJ of heat obtained from burnt fuel) of these biomass fuels are also given in Table 3. Total pollutant concentrations were converted from mg m^{-3} to mg MJ^{-1} by considering needed air volume for per mass of each fuel burning and calorific values [7,8]. As seen from Figs. 4–6 and Table 3 that the minimum CO, NO_X and SO_2 emissions were determined for wood shavings and kernel removed corncob, respectively. In addition, it is obvious from these figures and Table 3 that peanut shell has high total emissions when compared with other biomass fuels. On the contrary, kernel removed corncob has less NO_X and SO_2 emissions. The soot emissions of biomass fuels mentioned above are also seen from Fig. 7. As understood from this figure that all these fuels have similar soot emissions. There is no any soot emission differences between these fuels. CO, NO_X,

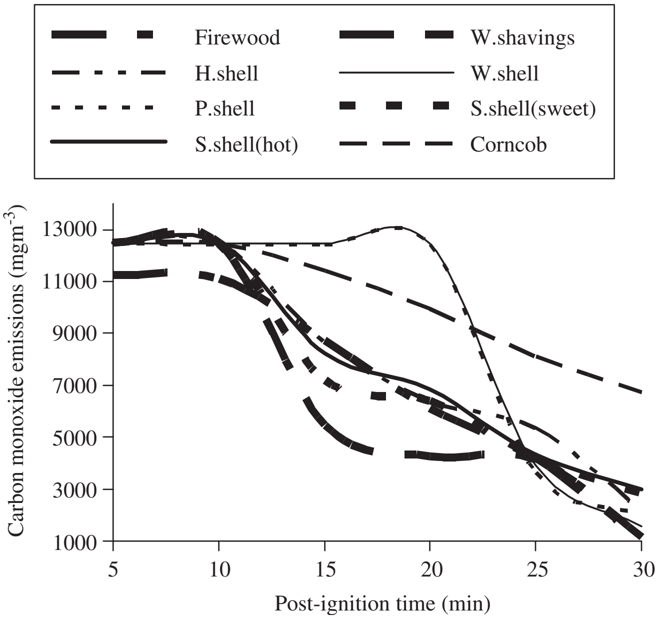

Fig. 4. Carbon monoxide emissions of selected biomass fuels.

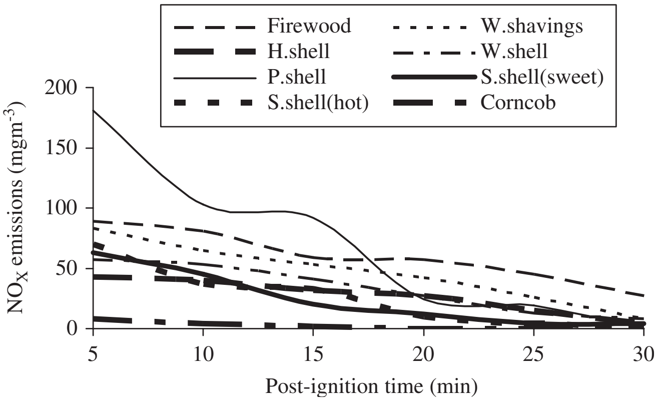

Fig. 5. Nitrogen oxides emissions of selected biomass fuels.

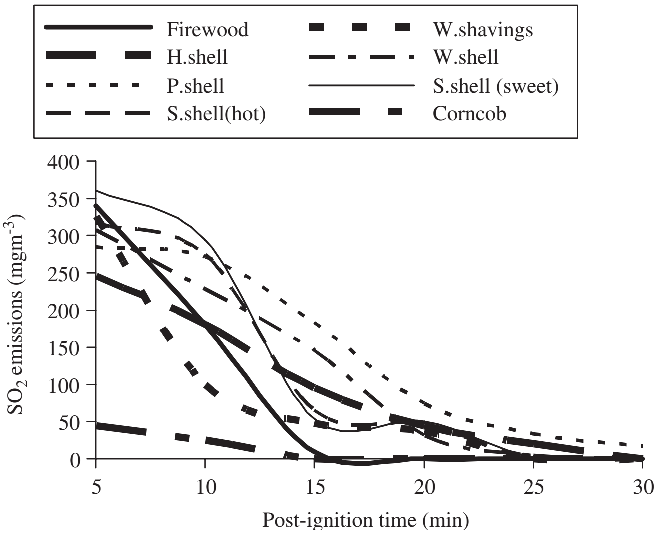

Fig. 6. Sulphur dioxide emissions of selected biomass fuels.

Table 3
Total emissions of selected fuels

Fuels	Carbon monoxide ($mg\,MJ^{-1}$)	Nitrogen oxides ($mg\,MJ^{-1}$)	Sulphur dioxide ($mg\,MJ^{-1}$)
Firewood	1489	12.54	19.00
W. shavings	1403	9.72	17.89
H. shell	1667	5.65	20.52
W. shell	2445	8.78	31.65
P. shell	2422	18.32	37.72
S. shell (sweet)	1405	4.52	23.26
S. shell (hot)	1449	4.77	21.49
Corncob	3276	0.75	3.75
Charcoal	2095	2.62	0

SO_x emissions and mass particulate emission regarding conventional woodstoves are also given 230.8 $lb\,ton^{-1}$ (5227 $mg\,MJ^{-1}$), 2.8 $lb\,ton^{-1}$ (63.42 $mg\,MJ^{-1}$), 0.4 $lb\,ton^{-1}$ (9.1 $mg\,MJ^{-1}$) and 18.5 $g\,kg^{-1}$ (1.68 $g\,MJ^{-1}$), respectively, by EPA [3–5].

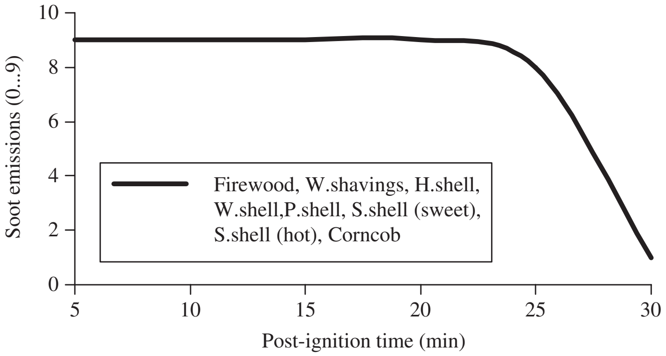

Fig. 7. Soot emissions of selected biomass fuels.

The emission results regarding wheat stalk litter (for cattle and sheep pen) and cornhusk and maize stalk litter (for cattle pen) are given in Table 4. Since these biomass fuels burned quickly, only two measurements could be done during each experiment.

The CO, NO_X, SO_2 and soot emissions about charcoal are seen from Figs. 8–10 and Table 3. Of the biomass fuels tested, the charcoal has the least total flue gas emissions. The total charcoal emissions of CO, NO_X, SO_2 and soot are 2095, 0, 2.62 $mg\,MJ^{-1}$ and 2.5, respectively (Fig. 10 and Table 3). Total charcoal NO_X and SO_2 emissions are significantly less when compared with other all experimented biomass fuels. This information is also confirmed by other literatures [6,14].

The thermal efficiency of the stove was calculated for several biomass fuels with post-ignition burning time of more than 30 min. This is because the surface temperature measurements needed a great deal of time, and it is obvious from the equations regarding thermal efficiency that fuel type has no important role on the efficiency. The average thermal efficiency of the stove was found approximately 46%. This value is high when compared with other stoves investigated in different literatures, and the tested stove is classified into the improved category [1,10,15]. Thermal efficiency of conventional woodstoves is also given as 54% by EPA [3,4].

4. Conclusions

According to the test results, the following inferences can be derived:

1. Firewood, wood shavings, hazelnut shell, walnut shell, peanut shell, seed shell of apricot (sweet and hot seed type) and kernel removed corncob have similar and high soot (8) emissions.
2. Peanut shell has more and corncob has lower flue gas emissions when compared with other biomass fuels (except charcoal).
3. There is not too much total emission difference between firewood, wood shavings, hazelnut shell, walnut shell and seed shell of apricot.

Table 4
Emissions of livestock litter

Fuels	Carbon monoxide ($mg\,m^{-3}$)		Nitrogen oxides ($mg\,m^{-3}$)		Sulphur dioxide ($mg\,m^{-3}$)		Soot (0–9)	
	Post-ignition time (min)							
	5	10	5	10	5	10	5	10
W sl (for cattle pen)	12 490	4750	59	17	148	17	9	9
Chmsl (for cattle pen)	12 445	3785	66	14	114	21	9	9
W sl (for sheep pen)	12 340	4916	49	11	162	24	9	9

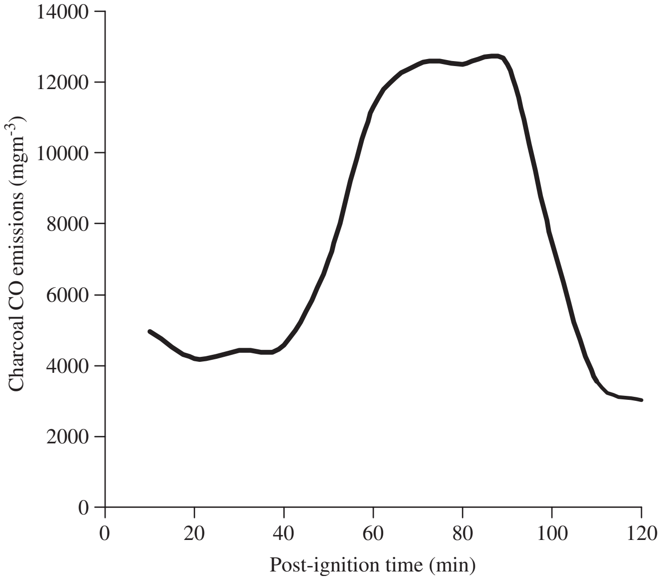

Fig. 8. Carbon monoxide emissions of charcoal.

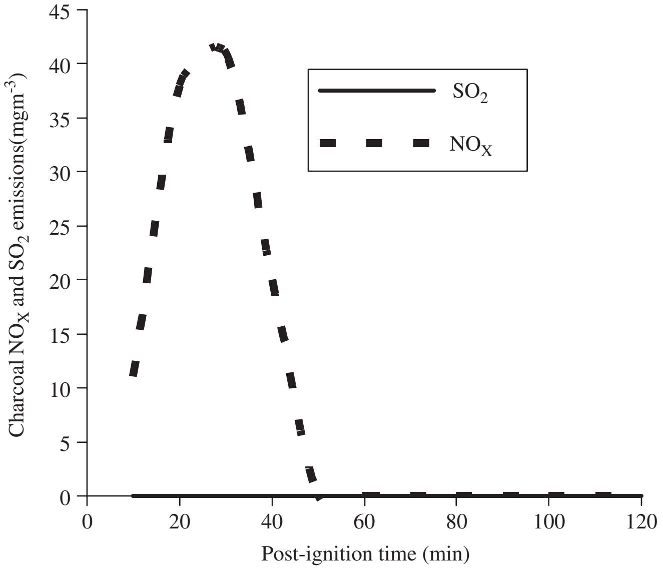

Fig. 9. Nitrogen oxides and sulphur dioxide emissions of charcoal.

4. Charcoal is the most appropriate biomass fuel for use in the biomass stoves because its combustion emits less smoke and NO_X and SO_2 flue gas emissions.

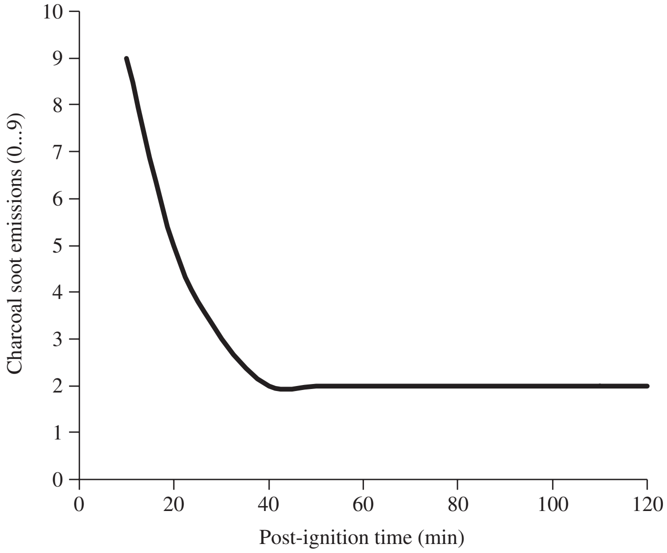

Fig. 10. Soot emissions of charcoal.

5. Because of the high carbon monoxide emissions of this stove with all of the fules tested, it cannot be used in enclosed spaces.
6. Thermal efficiency of the experimented space-heating biomass stove is approximately 46%, and it is classified into the improved category.

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